Turbulence Dynamics in Irregular Breaking Waves

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LONG-TERM GOALS

My long-term goals are to provide a detailed picture of the breaking and decay of irregular waves in a laboratory surf zone, and of the generation and evolution of related turbulent flow fields.

OBJECTIVES

The objectives of this project are:

1. To understand the effects of incident wave spectrum on the spatial and temporal distributions of wave breaking and the dynamics of turbulence in the surf zone.

2. To study the effect of offshore bars on the wave breaking process.

3. To elucidate the properties of wave breaking induced vortex structures.

APPROACH

A 25 m long, 0.75 m wide and 0.75 m deep tilting flume will be purchased and installed in the Fluid Mechanics Laboratory at South Dakota State University. This flume will be equipped with a programmable random wave generator that has active wave absorption to minimize long wave reflection from the wave paddle. Irregular waves will be generated and wave breaking will be induced on a plane slope. Submerged solid objects will be installed on the slope to represent natural bars. The experiment will involve detailed measurement of water surface elevation and flow circulation inside the surf zone using an array of capacitance wave gages and an Acoustic Doppler Velocimeter, measurement of turbulence velocity on a grid using a three-component Laser Doppler Anemometer, measurement of instantaneous three-dimensional velocity field in a plane under the breaking waves using a stereoscopic Particle Image Velocimetry system, and videotape recording of the surf zone. Laboratory experiments will be carried out over a wide range of incident wave conditions developed from the TMA spectrum by varying the significant wave height, peak period and spectral width parameter. The measured data will be used to improve our understanding of the dynamics of surf zone turbulence through an experimental investigation of the Reynolds-averaged momentum and energy equations, to obtain dissipation rates and turbulent stresses under breaking waves, to determine the ensemble average properties of the surf zone flow field, and to elucidate the spatial and temporal structures of surface breaking-induced vortices.

It is anticipated that the new wave flume will be operational in summer 2001. Presently, we are analyzing data from four irregular breaking wave experiments obtained in a wave flume at Texas A&M University. The completed experiments involved two different wave spectra (broad banded and narrow banded spectra) on two different beach profiles (plane beach and barred beach). Future experiments will be planned in light of the results of these experiments.

WORK COMPLETED

We have analyzed the characteristics of turbulence created by a broad-banded irregular wave train breaking on a 1:35 slope (Ting, 2000). Water particle velocities were measured simultaneously with wave elevations at three cross-shore locations inside the surf zone. The measured data were separated into low frequency and high frequency time series using a Fourier filter. The measured velocities were further separated into organized wave-induced velocities and turbulent velocity fluctuations by ensemble averaging. Videotape recording of the surf zone was employed to determine the percentage of breaking waves at each cross-shore location. A wave-by-wave analysis was carried out to obtain the probability distributions of individual wave heights, wave periods, peak wave velocities, and wave-averaged turbulent kinetic energies and Reynolds stresses. The vertical structure of the undertow, and the velocity profiles under the low-frequency waves were obtained. The correlations between turbulent kinetic energy and fluid velocity were determined from the measured data.

RESULTS

The broad-banded irregular wave train created a wide surf zone that was dominated by spilling type breakers. The incident waves had a significant wave height to wavelength ratio in deep water equal to those of the regular spilling breaker in Ting and Kirby (1996). Probability distributions of wave-averaged turbulent kinetic energy showed that the highest one-third wave-averaged turbulent kinetic energy values from the irregular waves were comparable to the time-averaged values from the regular waves. It was found that the correlation coefficient of the Reynolds stress varied strongly with turbulence velocity. Figure 1 is a plot of $\langle u'w'\rangle/(\langle u'^2\rangle \langle w'^2\rangle)^{1/2}$ versus $\langle u'^2/2\rangle$ and $\langle w'^2/2\rangle$, where the angular brackets denote an operator to take an ensemble average. In this figure, the range of $\langle u'^2/2\rangle$ and $\langle w'^2/2\rangle$ from 0.0 to 0.01 m^2/s^2 has been divided into ten equal class intervals forming 10×10 two-dimensional cells. The contour values represent the average values of $\langle u'w'\rangle/(\langle u'^2\rangle \langle w'^2\rangle)^{1/2}$ within the individual cells. Good correlation is found where the turbulence velocity is large; the correlation coefficient between u' and w' is about 0.3–0.5. These values are similar to the correlation coefficient of 0.4 observed in most turbulent shear flows. Time series analysis showed that correlation coefficient decreased over a wave cycle, and with distance from the water surface.

Figure 2 shows the time average correlations between the horizontal velocity and the turbulent kinetic energy at three cross section locations inside the surf zone. The results show that turbulent kinetic energy is transported landward by turbulence and short wave velocity, and seaward by the undertow. Cross-shore transport of turbulent kinetic energy decreases with distance from the water surface, due to decrease in the turbulence intensity and increase in the phase lag between the horizontal velocity and turbulent kinetic energy from the surface downward. Note that low-frequency waves can transport turbulent kinetic energy either onshore or offshore, depending upon the location inside the surf zone. Close to the bottom, the net cross-shore transport of turbulent kinetic energy is dominated by the undertow and is seaward. These results are consistent with those observed in the regular spilling breaker in Ting and Kirby (1996).

IMPACT/APPLICATIONS

The results of this project will be two-fold:

1. A successful outcome of this project would be a detailed picture of the breaking and decay of irregular waves in a laboratory surf zone, and of the generation and evolution of related turbulent flow fields on plane and barred beaches.

2. This project would provide the data needed to test and improve detailed models of surf zone breaking processes. This data set should be useful for testing a wide range of surf zone modeling techniques, including both present day models and models that are under long-range development.

TRANSITIONS

This project is complementary to other work such as the National Ocean Partnership Program (NOPP) to develop a community model of nearshore waves, current and bathymetric change. Other researchers may use the laboratory data collected in this project for integration, testing and improvement of their surf zone models.

RELATED PROJECTS

1. NSF Grant Number CTS-0078926, "Acquisition of a Multi-Purpose Open-Channel Flume for Water Flow Studies," Francis C. K. Ting et al, South Dakota State University. This equipment grant will provide partial funding for a new flume.

2. N00014-99-1-1051 (NOPP), "Development and Verification of a Comprehensive Community Model for Physical Processes in the Nearshore Ocean," James T. Kirby et al., University of Delaware. We will be working closely with Professor Kirby in the experimental design and the subsequent data analysis. We want to maximize the ability to fully test numerical models with experimental data. We also need Professor Kirby's computer simulations to improve our understanding of laboratory measurements.

REFERENCE

Ting, F. C. K. and Kirby, J. T. (1996), "Dynamics of surf zone turbulence in a spilling breaker," Coastal Engineering, Vol. 27, pp. 131-160.

PUBLICATION

Ting, F. C. K., "Laboratory study of wave and turbulence velocities in a broad-banded irregular wave surf zone," submitted to Coastal Engineering.

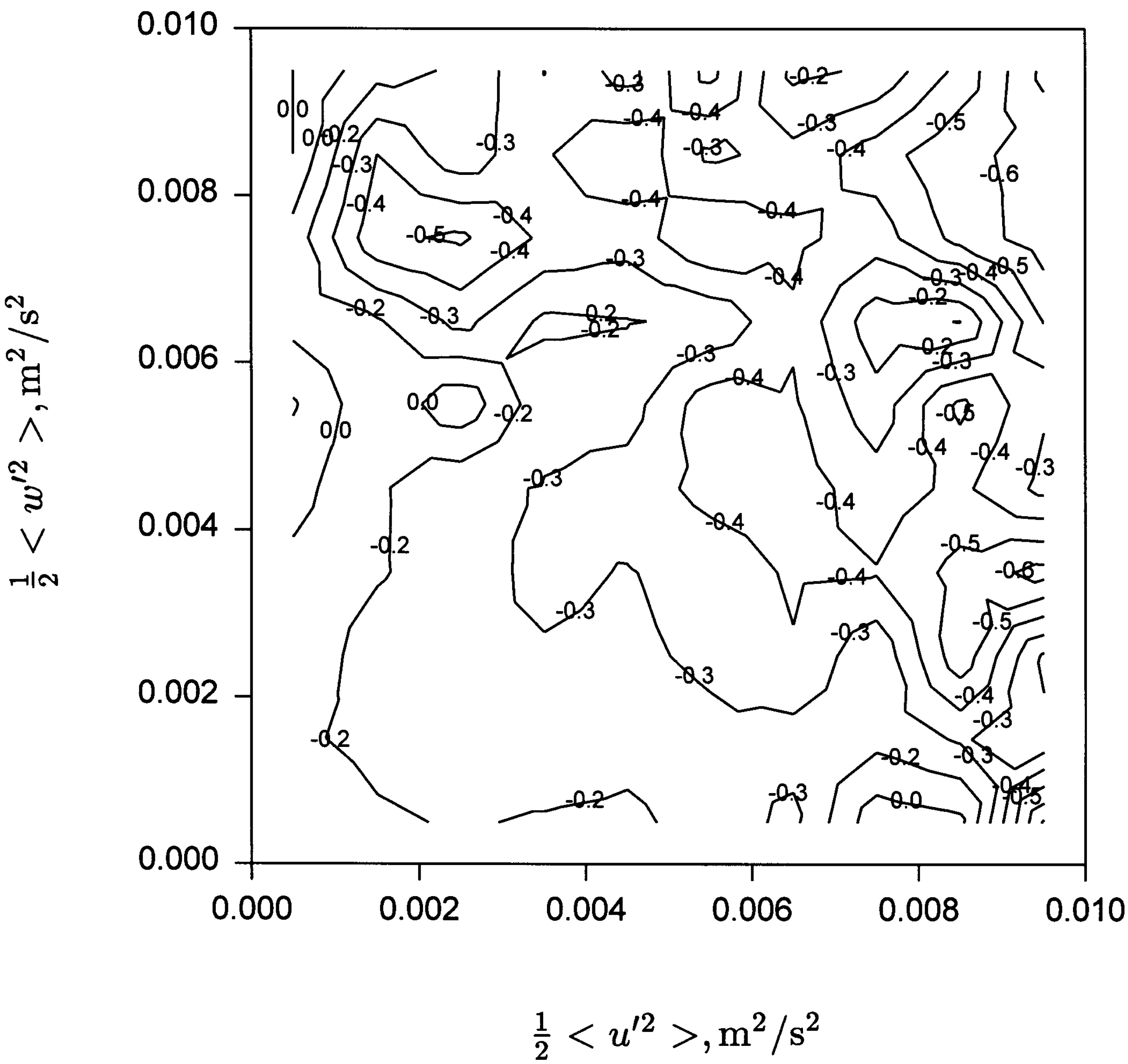

Figure 1. Variations of Reynolds stress correlation coefficient with turbulence energies inside the surf zone. The local still water depth was 13.72 cm and 57% of the waves were breaking. The velocity measurements were taken at 5 cm below the still water level.

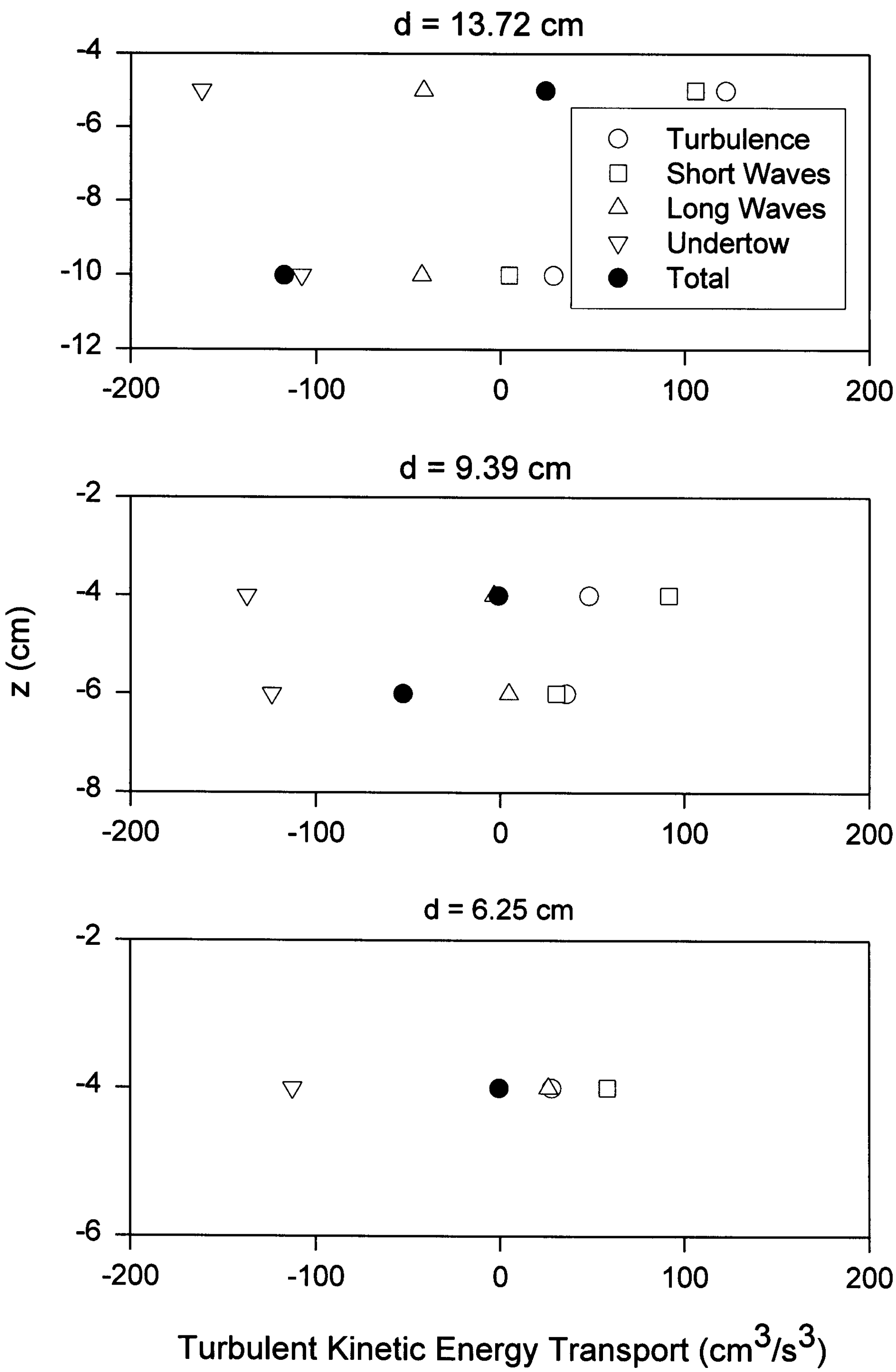

Figure 2. Distributions of time average correlations between turbulent kinetic energy and horizontal velocity at three cross-shore locations inside the surf zone. The percentage of breaking waves in the flow region investigated ranged from 57% to 94%.